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Hydropower Site Study at Imja Lake and Dingboche Village

by

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Report

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Contents

Introduction

This brief report combines background data on Imja Lake with information on GLOFs and micro-hydro potential to assess the danger that Imja Lake poses to downstream villages and determines what benefits might be accrued from the controlled drawdown of the lake.

The paper discusses the following: dam site information, possible dam failure modes, possible dam stability or lake drawdown solutions, costs of possible solutions, the applicability of hydropower to these solutions, the cost of adding a hydropower component to these solutions, and ultimately, estimates of benefits and costs for adding hydropower to Dingboche or other villages near Imja Lake that could benefit from a controlled drawdown of the lake.

Dam/Reservoir Site Background

Area Location Map

Imja Lake (or Imja Tsho) is located in the Nepalese Himalaya, about 9 km south of Mount Everest. The lake has experienced rapid growth in area and volume over the last 50 years, leading to concern of a catastrophic glacier lake outburst flood (GLOF) event. A GLOF could affect those villages that are nearby downstream such as the village of Dingboche, which is only 8 km downstream of the Imja Lake terminal moraine. Figure 1 shows the geographic locations of Imja Lake and Dingboche village.

Lake Characteristics

Imja Lake is bounded on the east by Imja glacier, on the north and south by lateral moraines, and to the west by a terminal moraine. Figure 2 shows the layout in an aerial photo from 2007.

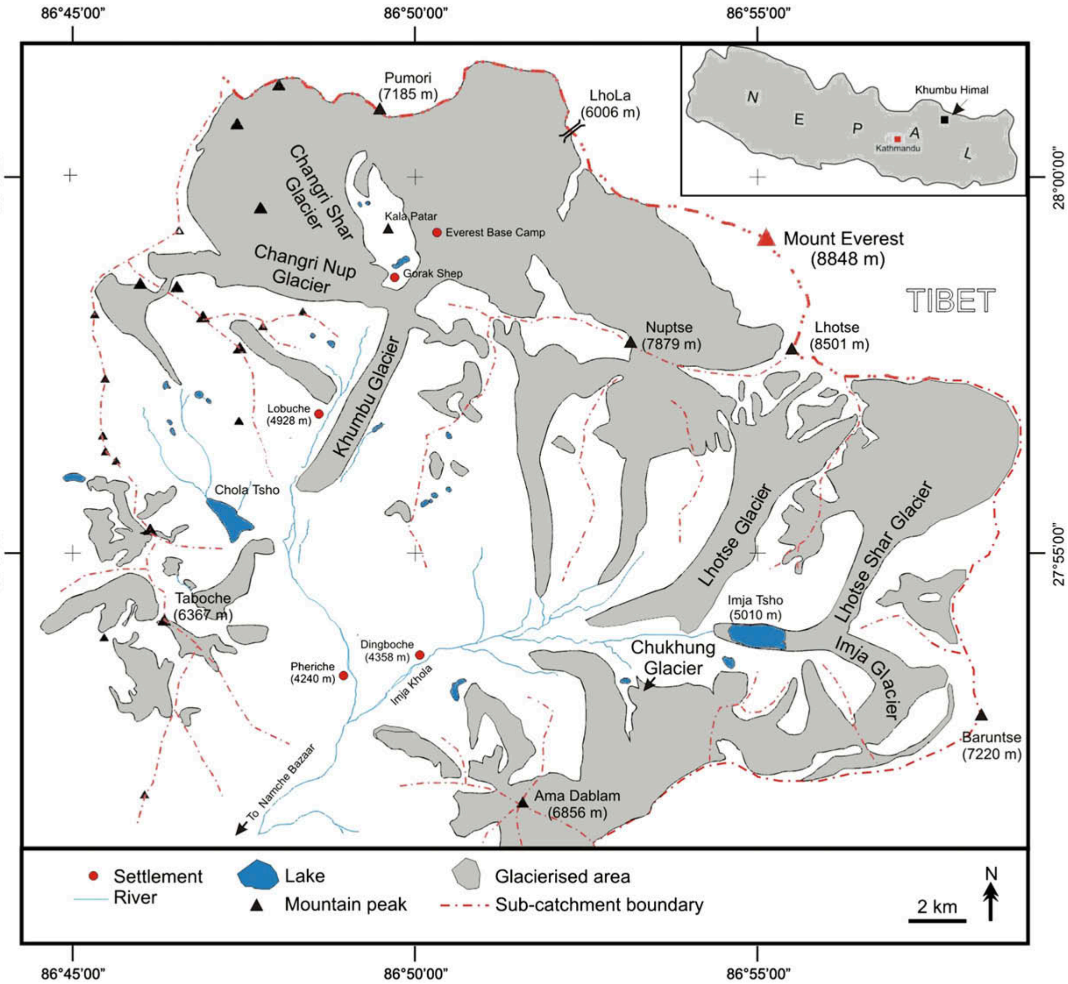

Figure 1 – Location Map (Hambrey et al., 2008)

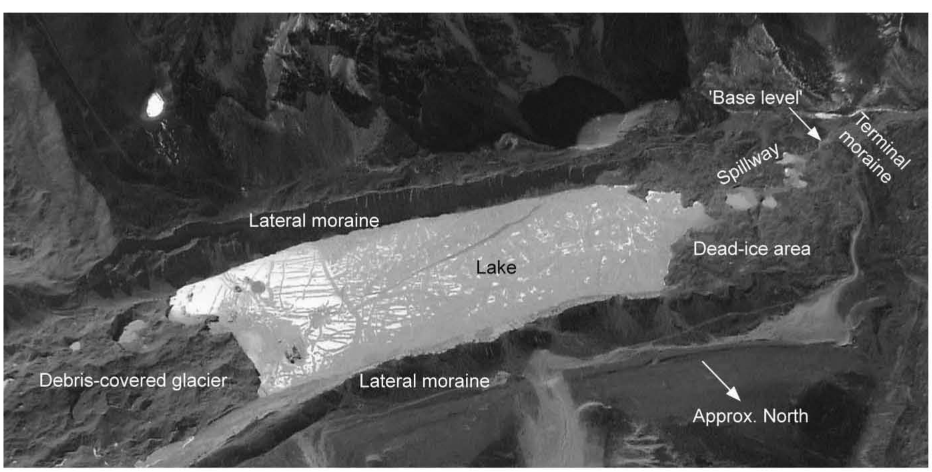

Figure 2 – Aerial Photo of Imja Lake (Watanabe et al., 2009)

The lake has developed rapidly from several supraglacial ponds in the 1950s to recent (2007) dimensions of 2000m in length and 650m in width (Watanabe et al., 2009). Figure 3 shows an estimated progression of the area from 1956 to 2007.

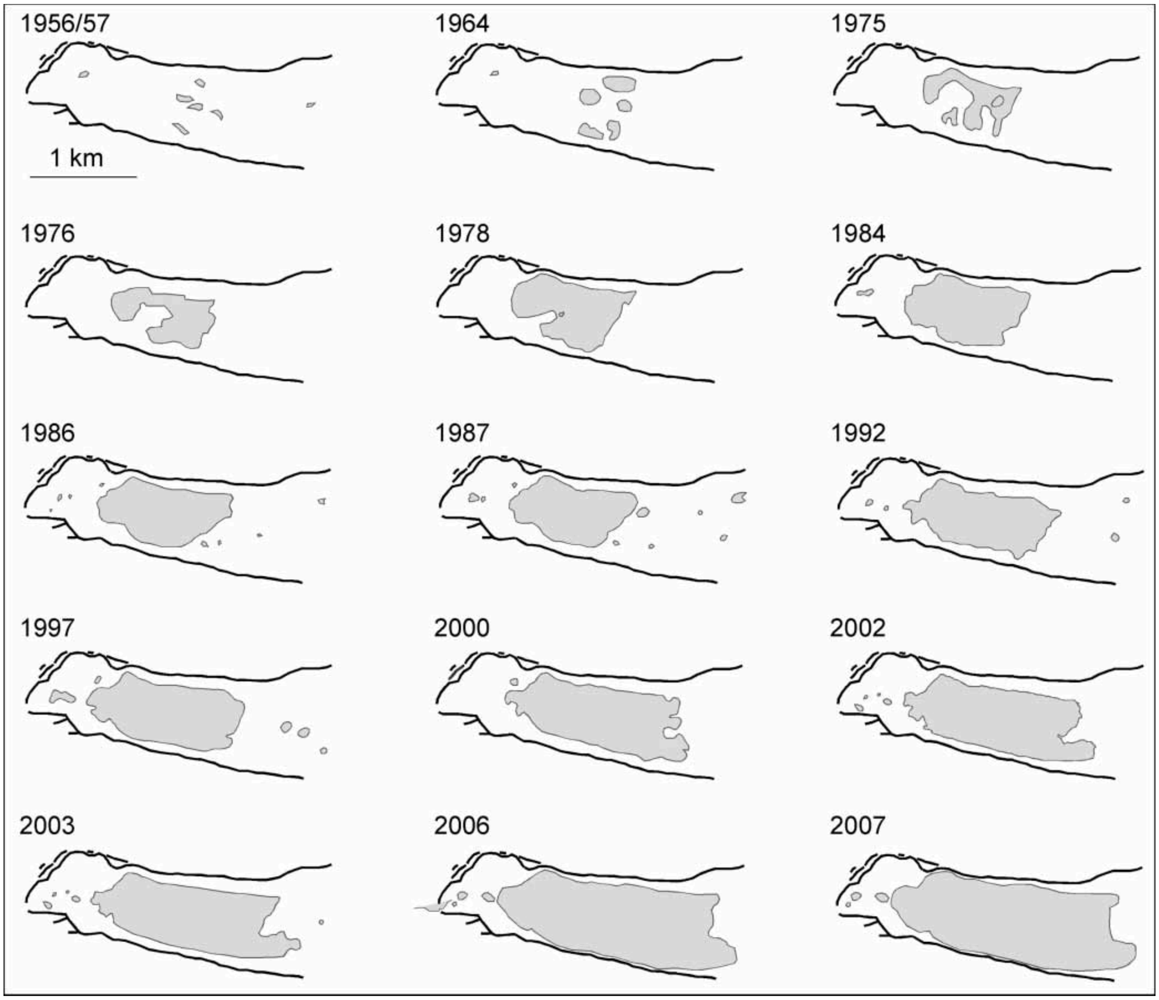

Figure 3 – Imja Lake Expansion 1956-2007 (Watanabe et al., 2009)

Although the lake has expanded rapidly in the last 50 years, expansion has occurred through calving of the eastern end of the glacier and not through movement of the terminal moraine (Hambrey et al., 2008). Figure 4 shows how the down-valley expansion has stabilized in recent years while the up-glacier expansion continues unabated.

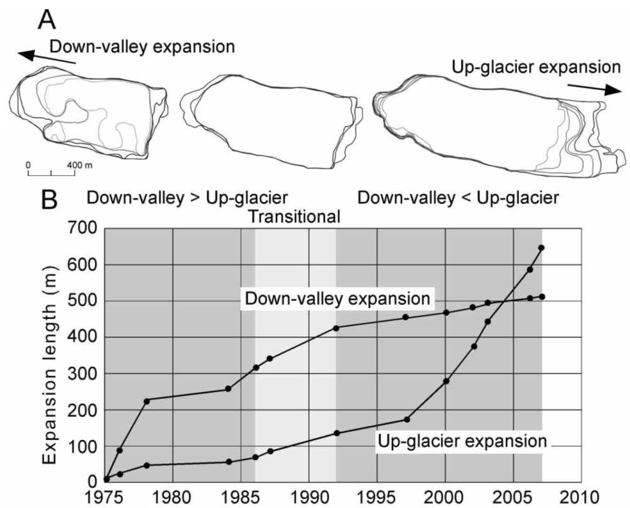

Figure 4 – Imja Lake Rates of Length Expansion (Watanabe et al., 2009)

Two expeditions were completed, one in 1992 and one in 2002, measuring the storage volume of the lake. Depth measurements at dozens of points dispersed throughout the lake were recorded by coring through the ice and using a tape measure to record the depth. The points were referenced via GPS to a defined datum (Sakai et al., 2005). Table 1 provides the tabulated results of the 1992 and 2002 data measurements. Note that the error in the table in the original paper of Sakai et al. (2005) has been corrected here so the stored water is multiplied by 10^6 m^3, not 10^9 m^3.

Table 1 - Imja Lake Characteristic Comparison, 1992 and 2002 (Sakai et al., 2005)

Measurement Year	April 1992	April 2002
Average depth (m)	47.0	41.6
Maximum depth (m)	99	90.5
Area (x 10^6 m^2)	0.60	0.86
Stored water (x 10^6 m^3)	28.0	35.8

Terminal and Lateral Moraines

The terminal moraine is about 700m wide and 50m high with a dead-ice core (Watanabe et al., 2009). The moraine has sparse vegetation and numerous kettle holes and ponds. The lake level inside the moraine is about 40 m below the lowest point on the crest. Drainage from the lake, and hence the entire glacier, is focused on a single channel that winds its way between the hummocks (Hambrey et al., 2008). Figure 5 gives a general idea of the size and geology of the terminal moraine.

Figure 5 – Terminal Moraine (Hambrey et al., 2008)

The minimum relative height between the lake level and the lateral moraine crest is 47m and increasing (Watanabe et al., 2009). Figure 6 shows the average height of the lateral moraine crests relative to the Imja Lake water surface in 1964, 1984, and 2006. Note that the lateral moraine troughs also act as gutters, trapping debris derived from rockfall, snow avalanches and fluvial transport (Hambrey et al., 2008).

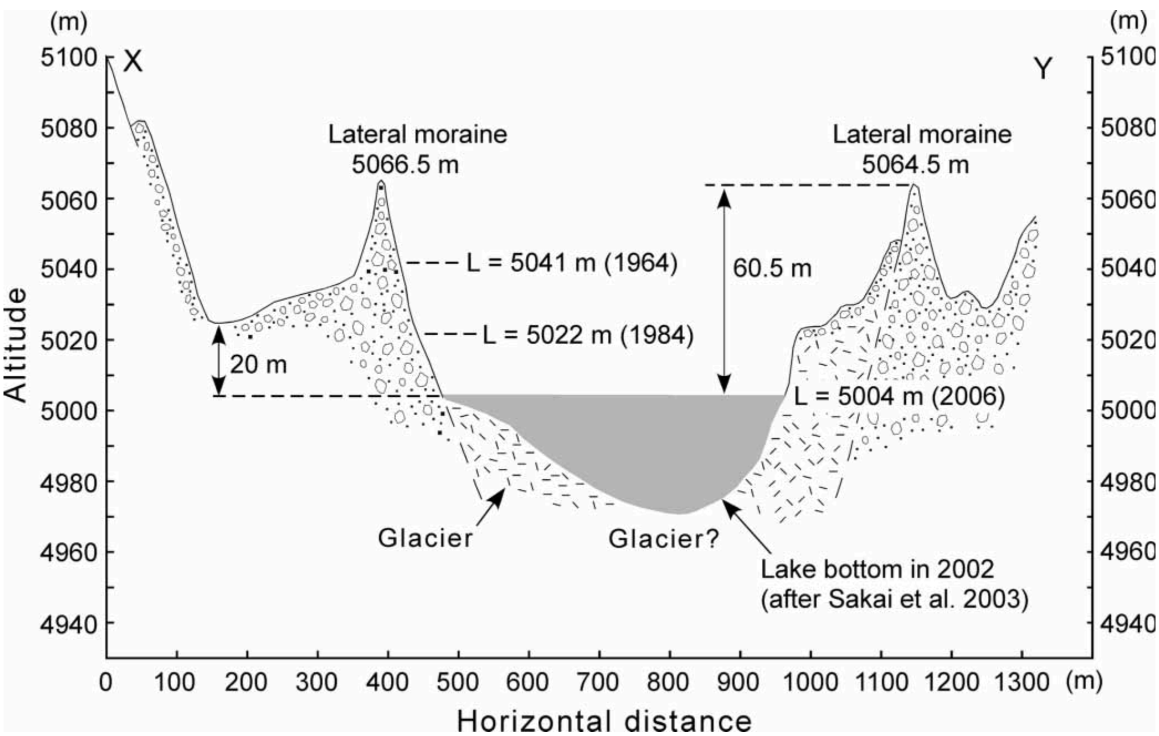

Figure 6 – Lateral Moraine Crest Elevations (Watanabe et al., 2009)

Hydrology Assumptions

Expected outflow through natural channel/spillway

The Imja Lake outflow is assumed to be one of the main components of river flow at Dingboche village. A recent report (Dingboche Bituyut Co., 2009) mentions a required flow rate of 300 liters per second, or 0.3 m^3/s, for the operation of two 100 kW hydro turbines. For the purposes of this report, the flow rate through the natural channel is assumed to be at least 0.3 m^3/s. This value needs to be verified in the field if any hydropower scheme at the lake site is to be pursued in greater detail.

Precipitation

The Nepalese government publishes precipitation data at multiple gage sites throughout Nepal. There are four precipitation gages in Solukhumbu District alone, site of Imja Lake and Dingboche Village. However, the data is not freely accessible without payment to the government. Precipitation data is not necessary for this report.

Seasonal Runoff

The site is assumed to be available for energy production for five months of the year at both Imja Lake and downstream at Dingboche village. A 2009 paper by Teiji Watanabe, et al., references GLOFs occurring between June and October, from which one might infer that the lakes are frozen the rest of the year. This needs to be verified in the field if any hydropower scheme at the lake site is to be pursued in greater detail.

Site Problem

Failure modes

The dangers of GLOF include: lake area and lake-area expansion rate; up-glacier and down-valley expansion rate; dead-ice melting; seepage; lake water level change; and surge wave by rockfall and/or slide and ice calving. In the case of Imja Lake, risk of GLOFs from rock and/or ice avalanches and failure from the surrounding area are minimal because of the wide valley configuration, i.e., the surrounding source area is far away from the lake and the high lateral moraines (Watanabe et al., 2009).

As the dead-ice area melts from a combination of both air temperature and lake water discharge, the terminal moraine continues to decrease in altitude, or sink. The altitude where the spillway channel cuts through the terminal moraine has remained stable at about 4992m for the past several years. The lake level was 5004m in 2006. If the dead ice were to continue melting and if the western shoreline reached the same altitude as the spillway channel, then the lake could burst (Watanabe et al., 2009).

Current estimates are that more than 100 years would be needed for the western shoreline of the lake to reach the terminal moraine elevation. However, this prediction is highly uncertain. It does seem accurate enough that there is no immediate danger of the lake draining due to expansion (Watanabe et al., 2009).

Seepage

Down-valley expansion may develop conditions favorable for seepage to occur. Seepage could occur through the surrounding moraines where their altitude is lower than the lake level. In the case of Imja Lake, the terminal moraine and dead-ice area are of greatest significance and the lateral moraines can be ignored as the lake water level is much lower than the base of the lateral moraines. As the dead-ice melts, the total volume of water below the terminal moraine increases, raising the possibility of triggering a GLOF by seepage, especially along the spillway. No signs of seepage were found during repeated visits to the study site between 1989 and 2006 (Watanabe et al., 2009).

Surge Waves

GLOFs are frequently triggered by surge waves, which in the case of Imja Lake could be caused by rockfall and/or rock slide from the lateral moraines and by ice-cliff collapse. The nearly 50m vertical elevation of the top of the lateral moraines above the lake level makes it unlikely that a surge wave would overtop them. However, a wave could more easily overtop the spillway region of the lake near the terminal moraine. Such an event would be uncommon as the lake elongates, which would make it more difficult for a wave to travel the length of the lake with overtopping power. However, the danger of a GLOF due to overtopping remains a possibility (Watanabe et al., 2009).

Failure consequences

An Imja Lake GLOF simulation was completed in 2007. The resulting peak flow and maximum flood depth is shown in Figure 7.

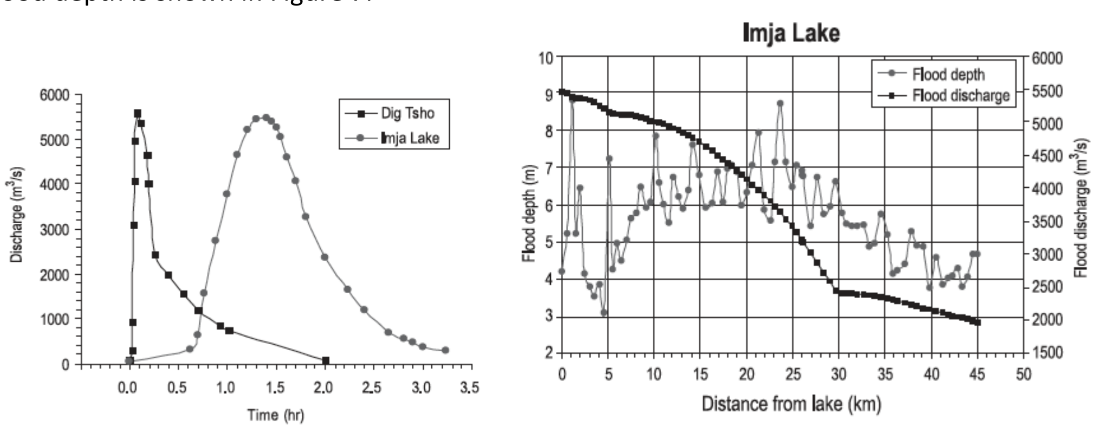

Figure 7 - Peak flow and maximum flood depth due to simulated Imja Lake GLOF (Bajracharya, Shrestha, and Rajbhandari 2007)

Dingboche village would see a flood depth of 5.8m about 14 minutes after the dam burst. The flood zone around the village would consist of considerable agricultural land and a few houses. The rest of the village would remain outside of the flood zone. Although the loss of life appears limited in this analysis, the damage to the villagers' livelihood is extensive (Bajracharya et al., 2007).

Site Solutions

Fortifying the Channel Spillway

As the danger of imminent failure is remote (Watanabe et al., 2009), the site solution for stabilizing the terminal moraine may simply be reinforcing the natural channel spillway. However, the presence of a melting ice core potentially makes reinforcement of the spillway difficult. The area around the natural channel spillway should be surveyed for nearby evidence of the ice core. If the core does not extend close to the natural spillway, then there should be little problem in reinforcing and expanding the natural spillway. However, if the core is close to the spillway, then stabilization may be impossible in the current location. Another spillway in a different, more stable location may be prudent depending on ice core conditions. The sizing of any spillway would be dependent on precipitation forecasts and melting rates of the Lhotse Shar and Imja glaciers. A spillway sizing estimate is not included in this report.

Siphon

Siphons have been used on numerous lake lowering projects around the world as an initial way to stabilize a lake water level, for example at Hualcán glacier lake (Lake 513) in Peru in the late 1980s. Siphons were used to lower the lake level by about 5m, although the siphons supposedly could have lowered the lake level by 8-12m if necessary. Siphon capacity was around 0.5 m^3/s (Reynolds et al., 1998). At that discharge rate, assuming 5 months of operation and no inflow, Imja Lake could be completely drained in about 5 years, although the lake depth would make complete drainage impractical. It is possible to drain the lake even faster if the lake doesn't freeze to a depth that leaves the siphon inoperable for part of the year. Year-round siphon operation would allow the lake to be drained in a little over 2 years, but again, this would be impractical given the depth of the lake and the limitations on siphon capabilities.

The maximum lift of a siphon depends on altitude, flow velocity, and pipeline losses. As the siphon draws down the lake level, the absolute pressure at the highest point of the siphon approaches the vapor pressure of water. When the absolute pressure reaches the vapor pressure of water for the given altitude, cavitation occurs and the siphon tension is broken. The maximum lift of any siphon concept would need to be explored further in a more detailed feasibility study.

The volume that can be practically drained is unknown because of a lack of incremental elevation-volume data at the lake. The average depth is around 40m, so a siphon draining the top 12m would be expected to drain at least 30% of the lake volume based on typical lake elevation-volume relationships (volumes typically increase rapidly at the highest storage elevations due to each successive contour having a larger area than the lower one, so the top 1/3 elevation of the lake should contain at least 1/3 of the volume of the lake). Despite limitations, siphons should be considered as an initial step of water level stabilization because of quick results that can be measured in months.

As the lake level approaches the crest of the terminal moraine, a potential siphon option becomes more economically attractive too. Constructing an artificial channel in the terminal moraine would allow the siphon piping to be installed and operational immediately. As discussed in the channel spillway alternative, any artificial channel construction in the moraine should avoid the ice core for stability reasons. Installation of a siphon would allow a controlled release of water for at least 5 months of the year, and maybe year-round, with potential hydropower benefits at the site (to be discussed later).

Drainage Tunnel

A drainage tunnel is a proven technology that has been used in the Andes to alleviate GLOF concerns. The concept involves constructing a tunnel at the base of the lake and connecting it to a point downstream on the river. The lake can then be drained in a controlled manner. Figure 8 shows the drainage concept used at Lake 513 in Peru. The tunnel diameter is two meters. The staggered lake outlets allow drainage to continue in case one of the outlets is blocked and also allow for the flow to decrease over time as the water level falls. The water level of Lake 513 in Peru was safely lowered more than 20m in less than 2 years (Reynolds et al., 1998).

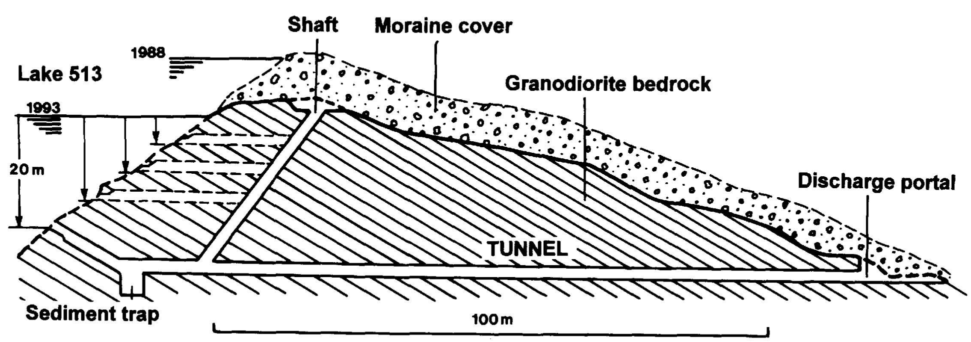

Figure 8 – Drainage Tunnel Concept (Reynolds et al., 1998)

The tunnel should be sized to drain the lake to safe levels in a short enough time period that the distance between the moraine crest and the lake level do not become dangerously close, as defined by a calving of a glacier or rock slide causing a seiche with a height that exceeds the moraine crest. Drainage flow must be limited so as not to cause downstream flows that exceed normal monthly maximum flows. Exceeding these flows may disturb the river ecology, damage downstream infrastructure or cause preventable flood conditions for downstream users.

Soft Cost/Benefits of Site Solutions

Channel Spillway

Constructing a channel spillway would require mechanical excavation equipment at the very least, and probably equipment used for drilling and blasting. The actual spillway would need to be made of concrete and thus require the necessary equipment for construction of it. This equipment may need to be supplied via helicopter to the remote, high altitude site, a considerable expense. More information about the site and local construction costs are needed before even a rough order of magnitude cost estimate can be completed.

Even if the spillway is an economical alternative, it may be in danger of collapse from a seiche in the lake. As the ice-core at the center of the terminal moraine melts, the moraine crest will continue to lower relative to the water level. Presumably the spillway will lower with the moraine and continue to decrease water levels. However, differential settlement may occur, leaving the terminal moraine crest dangerously close in elevation to the water level. In such a scenario, the spillway may not offer an acceptable solution for the people downstream of the lake.

Siphon

Siphon equipment would probably need to be delivered via helicopter. The siphon would also require excavation of a channel and construction of a concrete apron to place the piping, similar to the channel spillway requirements. The siphon can lower water levels considerably, perhaps around 12m, but this may not be sufficient in terms of risk to the downstream communities. A GLOF analysis of the reduced lake volume after application of a siphon would need to be completed to determine if downstream communities are still at risk.

The siphon may also be constrained to operate for only half of the year due to lake freezing. The siphon at Lake 513 in Peru operated at least from October through June, but it is unclear if the siphon operated year-round. If operation must be halted during the winter, then it must also be re-started each year. Re-starting the siphoning process could require some power generating equipment to be sent to the site each year.

Drainage Tunnel

A drainage tunnel would be the most expensive alternative but also the most effective solution at Imja Lake. The tunnel would, at a minimum, require drilling and blasting equipment. Poor geologic conditions could also require that the tunnel be heavily reinforced. Geologic testing would need to be completed to determine an optimal route and design. The tunnel should probably feature multiple outlets at various elevations, as shown in Figure 8, for redundancy.

Dingboche Village Characteristics

Background

The population of Dingboche is around 200 people, or about 50 households. Most households depend on agriculture as their main source of livelihood. The village also happens to be along the trekking route to the Everest basecamp, known as the "Khumbu Trekking Route." There is potential for tourist development in Dingboche, be it in the form of hotels, restaurants, equipment, porters-for-hire, etc.

Electricity Opportunities

Dingboche is located on the Khumbu Trekking Route to Everest basecamp, which means that many visitors pass through the village yearly. At this time, the yearly number of visitors and the number of visitor nights in Dingboche is unknown. From the website khumbutrekking.com, it appears that most visitors include an overnight stay in Dingboche for acclimatization purposes. Visitors from more developed countries are accustomed to readily available electricity and would have many uses for electricity at Dingboche. Visitors are also capable of paying higher tariffs for power than the villagers can afford.

Assuming each household uses 100 watts of electricity, the total village demand for lighting would be 5 kW. The usage estimate is in line with three case studies of micro-hydro schemes in Nepal that give a range of 103-444 watts per household (Dhungel 2009). However, the 2009 Dingboche Bidhyut Co. desk study calls for a hydropower capacity of 200 kW, with the difference presumably being used by tourists and the tourist industry.

Hydropower Recovery Options

A previous study by Dingboche Bidhyut Co. (2009) was meant to determine the potential energy recovery from a proposed irrigation pipeline near Dingboche village. Dingboche Bidhyut Co. was incorporated to study the installation of an energy generation facility at or near Dingboche village. The study itself is more of a request for proposal outlining exactly what companies would have to provide from a design and construction cost standpoint to advance the energy generation project. However, the study also contains some valuable input parameters that at this time are the most reliable data available to the authors for the site. Per the study, the alternatives discussed below are all assumed to provide on the order of 200 kW installed capacity.

Siphon turbine at Imja Lake

A siphon turbine could be placed at the terminal moraine at Imja Lake. The siphon concept is shown in Figure 9.

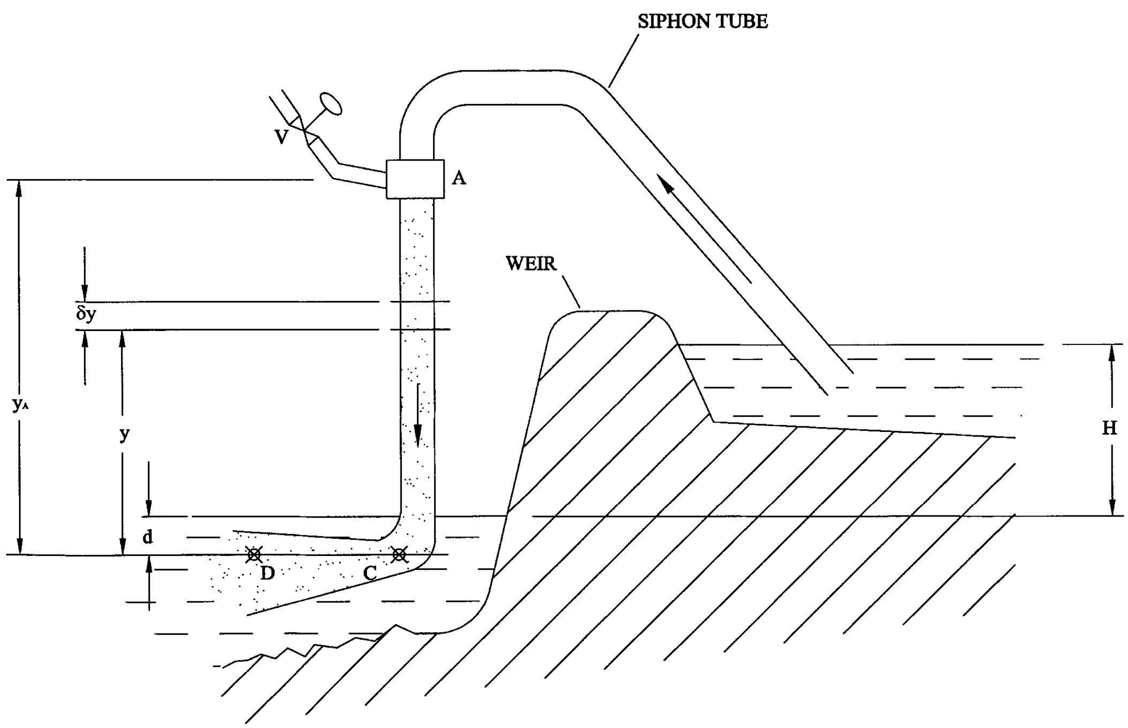

Figure 9 – Siphon Turbine Concept (French and Widden 2001)

Incorporating a turbine into a siphon used for lake drainage could mean low incremental costs for installation of the turbine since many components of the siphon would need to be constructed regardless of the presence of a turbine.

Siphon turbines would be capable of providing 200 kW of electricity to Dingboche village. The turbines come in a variety of capacities and head ranges as shown in Figure 10. The feasible head difference (maximum lift) appears to be about 15m for non-cascade situations, although the Figure likely assumes conditions at sea level. The high altitude at Imja would reduce the maximum lift capability of the siphon. Maximum capabilities would need to be confirmed by the manufacturers. Imja Lake has an average depth of 40m, so a significant volume of water, estimated to be at least 35% of the lake, could be drained via a siphoning approach. Please see the section Soft Cost/Benefits of Site Solutions, sub-heading Siphon for an explanation of the volume estimates.

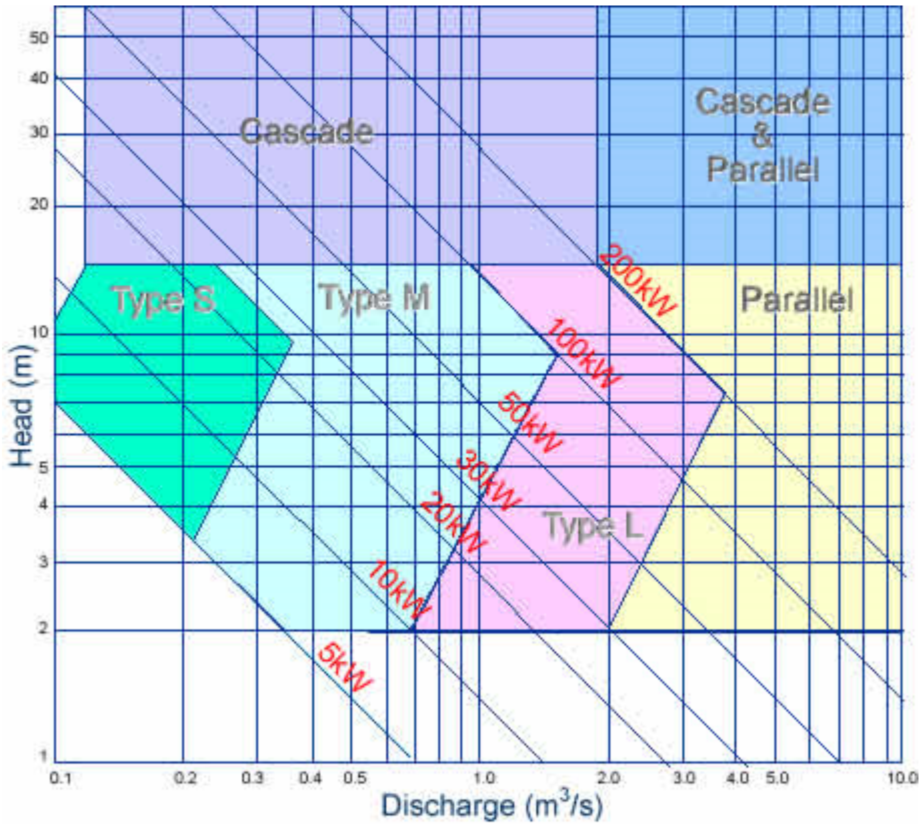

Figure 10 – Siphon turbine performance for Toshiba Hydro eKids (Toshiba Engineering, 2002)

Turbine at end of drainage tunnel near Imja Lake

Placement of a turbine at the end of the drainage tunnel could be cost effective in that most of the costs would be necessary for construction of the drainage tunnel itself, leaving low incremental costs for the turbine. The turbine could be one or two small Francis units with a total installed capacity of 200 kW. The capacity and unit type are based on the 2009 Dingboche Bidhyut Co. study. Since the head at the drainage tunnel would be different than at the village, the capacity and unit type must be confirmed by a more detailed analysis. Nepal already has numerous small Francis units in operation and it is likely that the country's manufacturers have the capability to produce the units.

A hydraulic transient analysis would need to be performed before choosing units because of the possibility that a surge tank would be needed to be incorporated into the tunnel design.

Turbine at Dingboche village

The turbine concept at Dingboche village is the one discussed in the Dingboche Bidhyut Co. (2009) study. The concept is limited in details but appears to be a weir and holding pond being built upstream of the village, with a pipeline running downhill for an undetermined length that connects to two Francis turbines. The assumed design discharge of 300 lps (0.3 m^3/s) and design head of 95m is enough to generate roughly 200 kW of energy. Annual energy generation has been estimated at 1.65 GWh. Once water has passed through the turbines, it could be used for irrigation of 20 ha of land. It is also possible to consider a similar system for the Chukung village which is closer to Imja Lake.

Incremental Cost of Hydropower Alternatives

The following section presents preliminary cost estimates for constructing the hydropower alternatives or, for some alternatives, a methodology for estimating these preliminary costs. Only the incremental cost of adding hydropower should be considered in the cost estimates of these alternatives since the other infrastructure, such as a siphon or drainage tunnel, would need to be constructed in any case to alleviate GLOF concerns at the lake regardless of the hydropower potential.

The estimated cost of carrying out detailed feasibility and environmental studies for a hydropower project would be common to all hydropower alternatives. According to the Dingboche Bidhyut Co. (2009) study, the cost of the feasibility and environmental studies would be around Rs. 18,00,000, or about $25,558 at the exchange rate of 1 USD = 70.43 Nepalese Rs (as of 4/16/11). Note that the cost excludes any kind of construction and equipment costs.

Siphon Turbine at Imja Lake

Although a siphon turbine has the advantage of serving the dual purpose of drawing down the lake while providing hydropower generation, the cost of transporting the equipment to the site via helicopter may be quite expensive. It should also be noted that the siphon may only be able to operate during the 5-6 months when the lake is ice free. An intermittent energy source may not be as valuable as a year-round electricity source, such as a hydro turbine located at the village.

The cost of a 200 kW siphon turbine is difficult to estimate because manufacturers do not readily provide such estimates without first being contacted and informed about a potential project. Since this project is preliminary with so many unknowns, it was decided not to contact any potential manufacturers.

The siphon turbine would also require an estimated 8 km of transmission lines to connect the turbine to the village, to be discussed below.

Transmission Interconnection

The cost of transmission lines can be quite variable depending on terrain and capacity. Table 2 shows the costs per kWh as a function of distance from the grid for rural villages in India (Nouni et al., 2007). In the case of Dingboche village, the transmission line would not connect to a grid but rather just connect the village consumers to the turbine. However, since the costs shown in Table 2 are for electrifying small, rural villages in India, the table will be used as an initial estimate of transmission line costs at Dingboche.

Dingboche is about 8km away from the Imja Lake terminal moraine. Assuming a 0.6 load factor and peak load of 100 kW, the cost would be 0.64 Rs./kWh (0.009 USD/kWh).

The load factor estimate is based on similar villages in Nepal with micro hydro capacity. Daunekhola village has a 53% load factor and consists of 116 households using 12 kW of power. Tikhedhunga village consists of 12 hotels and 90 households and has 40 kW of power. The load factor is 90% during the early mornings and at night, but 0% for six hours during the day (Dhungel 2009). Based on these known load factors, a load factor of 0.6 has been estimated for Dingboche.

The cost/kWh should be inflated to end of year 2010 values. Nouni et al. (2007) was published in early 2007, so year-end 2006 prices will be assumed for the values reported in Table 2. The inflation rates by year are as follows:

2007 – 5.3%,
2008 – 6.4%,
2009 – 8.3%,
2010 – 10.9%

(http://www.indexmundi.com/india/inflation_rate_%28consumer_prices%29.html)

Using the above information, 0.64 Rs./kWh in 2006 equates to 0.86 Rs./kWh at the end of 2010. The exchange rate as of May 9, 2011 was 44.68 Rs. equal to 1 USD. Therefore, the estimated USD cost of connecting a turbine at Imja Lake to Dingboche village is 0.019 USD/kWh. Note that the estimate is for a peak load of 100 kW, which is half that expressed in the Dingboche Bidhyut Co. (2009) study. However, the lack of source data behind the pricing in Table 2 means that an extrapolation beyond 100 kW would be a complete guess. Since costs per kWh fall as capacity (in kW) increases, using the 100 kW capacity as a reference price will be conservative. Therefore, the cost/kWh for a 100 kW peak loading condition will be used as the price to connect Dingboche to the turbine at Imja.

Table 2 – Cost of distribution of electricity in hilly terrain in India (Nouni et al., 2007)

Distance of village from existing 11 kV line (km)	Peak load (kW)	Estimated cost of distribution of electricity (Rs./kWh) with a load factor of					
		0.1	0.2	0.3	0.4	0.6	0.8
5	5	46.61	23.3	15.54	11.65	7.77	5.83
	25	9.61	4.81	3.2	2.4	1.6	1.2
	63	3.91	1.95	1.3	0.98	0.65	0.49
	100	2.5	1.25	0.83	0.62	0.42	0.31
8	5	73.83	36.92	24.61	18.46	12.31	9.23
	25	15.06	7.53	5.02	3.76	2.51	1.88
	63	6.07	3.04	2.02	1.52	1.01	0.76
	100	3.86	1.93	1.29	0.96	0.64	0.48
10	5	91.98	45.99	30.66	23	15.33	11.5
	25	18.69	9.34	6.23	4.67	3.11	2.34
	63	7.51	3.76	2.5	1.88	1.25	0.94
	100	4.76	2.38	1.59	1.19	0.79	0.6
12	5	110.13	55.07	36.71	27.53	18.36	13.77
	25	22.32	11.16	7.44	5.58	3.72	2.79
	63	8.95	4.48	2.98	2.24	1.49	1.12
	100	5.67	2.84	1.89	1.42	0.95	0.71
15	5	137.36	68.68	45.79	34.34	22.89	17.17
	25	27.76	13.88	9.25	6.94	4.63	3.47
	63	11.11	5.56	3.7	2.78	1.85	1.39
	100	7.03	3.52	2.34	1.76	1.17	0.88
20	5	182.73	91.37	60.91	45.68	30.46	22.84
	25	36.84	18.42	12.28	9.21	6.14	4.6
	63	14.71	7.36	4.9	3.68	2.45	1.84
	100	9.3	4.65	3.1	2.33	1.55	1.16
25	5	228.11	114.05	76.04	57.03	38.02	28.51
	25	45.91	22.96	15.3	11.48	7.65	5.74
	63	18.31	9.16	6.1	4.58	3.05	2.29
	100	11.57	5.79	3.86	2.89	1.93	1.45

The estimated annual generation of two 100-kW turbines at Dingboche village is expected to be 1.65 GWh/yr (Dingboche Bituyut Co. 2009). Assuming the same generation capability is available at Imja Lake, the total cost of the transmission line would be $31,350 (USD). This cost has a high degree of uncertainty, but in the absence of any better cost alternatives, it is used as a starting point for cost comparisons between alternatives.

Francis Turbine at End of Imja Lake Drainage Tunnel

One or two small Francis turbines could be placed at the end of the drainage tunnel at Imja Lake. There are numerous worldwide and local Nepalese manufacturers of such turbines. The costs for such turbines vary widely. The best approach for costing such projects is to turn to previous projects or case studies with similar conditions.

Kennas et al. (2000) studied 16 micro-hydro projects in Sri Lanka, Nepal, Peru, Zimbabwe and Mozambique. The average installed cost of a micro hydro scheme for the purposes of electricity generation was found to be $3,085 per kW in 1998 dollars. Using the US Bureau of Labor Statistics' inflation calculator (http://www.bls.gov/data/inflation_calculator.htm) for the period from 1998 to 2011, we find that $1 in 1998 equals $1.37 in 2011. So the $3,085 cost per kW becomes $4,226 per kW installed in 2011 dollars. Note that these costs include transmission line costs for these sample projects.

An alternative cost estimate (Nouni et al., 2007) gives the capital cost of decentralized generation technologies deployed for sample projects in India. The capital cost range for small hydropower projects is 124,000-216,000 Rs./kW, or $2,775-$4,834/kW in 2006 USD (exchange rate of 44.68 Rs. per 1 USD, May 10, 2011). After accounting for inflation, the project cost ranges from $3,734-$6,505/kW. The average from Kennas et al. (2000) sample projects, $4, 226, fits within the bounds established by Nouni et al. (2007).

Using the Nouni et al. (2007) bounds, a 200 kW project at Imja Lake would therefore be expected to cost anywhere from $746,800 to $1,301,000, excluding transmission line costs, which would be the same as in the siphon turbine concept - $31,350. Including estimated engineering costs of $25,558, the total project cost would be expected to be anywhere from $804,000 to $1,358,000, or $4,019-$6,790/kW.

A third source of costs is Dhungel (2009) who studied three micro-hydro schemes in Nepal. The capital cost in Table 3 consists of all expenses for both equipments and services, from the planning phase until the commissioning of the system.

Note that without the subsidies and grants, the total cost of the three systems would be as follows:

Angakhola - $308/kW (5 kW system)
Daunekhola - $1,899/kW (12 kW system)
Tikhedhunga - $1,915/kW (40 kW system)

Assuming the Imja micro-hydro system follows the trend of more installed capacity equaling a higher cost per installed capacity (which can perhaps be explained by the complexity of the installed system), the project might cost around $2,000/kW on the low end, or $400,000 total.

Table 3 – Cost Characteristics for Three Micro Hydro Schemes in Nepal (Dhungel 2009)

MH System	Installed Capacity (kW)	Total Cost ($)	Subsidy ($)	Grant ($)	Financial Cost (Total cost – Subsidy Grant) ($)	Financial Cost per Installed kW ($)
Angakhola MH	5	1,538	462	0	1,077	215
Daunekhola MH	12	22,792	3,064	10,282	9,447	787
Tikhedhunga MH	40	76,582	14,508	38,967	23,105	578

Using $2,000/kW as the lower constraint, two Francis hydro turbines installed at Imja Lake may cost somewhere between $2,000 and $6,790/kW ($400,000 to $1,358,000).

Turbines at Dingboche Village (weir and penstock)

Siting turbines near Dingboche village per the Dingboche Bidhyut Co. (2009) study would save transmission line costs. The study is unclear but is assumed to consist of an upstream weir and pond, and a small pipeline of undetermined length running downhill to connect to two Francis turbines, each having a generating capacity of 100 kW. Design head would be 95m; design flow would be 300 liters per second, or 0.3 m^3/s (Dingboche Bidhyut Co. 2009). Using the cost bounds established by Nouni et al. (2007) less the transmission line costs, the total project costs would be expected to be anywhere from $772,358 to $1,326,558, or $3,862-$6,633/kW.

Using Dhungel's 2009 cost estimates as the lower bound, the total project costs could be anywhere from $2,000 to $6,633/kW.

O&M Cost Estimates

Dhungel (2009) provides the annual operating and maintenance costs of the three Nepal micro-hydro systems calculated on the basis of the annual salary of the manager and the operator of the systems, plus other maintenance costs as they are reported. Table 4 shows the O&M costs.

Table 4 – Annual O&M costs for Three Micro Hydro Schemes in Nepal (Dhungel 2009)

MH System	Operating Cost ($)	Maintenance Cost ($)	Total ($)
Angakhola MH	277	46	323
Daunekhola MH	554	684	1,238
Tikhedhunga MH	812	2,297	3,109

The micro hydro systems break down into O&M costs/kW as follows:

Angakhola - $65/kW /yr (5 kW system)
Daunekhola - $103/kW/yr (12 kW system)
Tikhedhunga - $78/kW/yr (40 kW system)

The average of the three systems is $82/kW/yr. This will be used as the annual O&M costs for the Imja/Dingboche system alternatives.

Estimated Benefits

Tourism

Providing reliable power will be a boon to the Everest area tourism industry. Trekkers should be willing to pay significantly higher rates than residents for the privilege of using electricity.

Irrigation

The irrigation of up to 20 ha of farmland should increase crop yields and benefit farmers.

Industrial Use

Dingboche village could benefit from an as yet undefined industrial use for its power. Similar Nepalese communities have installed agricultural processing units such as rice hullers or millers to make use of daytime power when residents are not utilizing the power (Dhungel 2009).

Household Uses

Lighting and operation of electronic equipment are the two main ways that each household can benefit from a steady supply of electricity. Residents could also potentially incur soft benefits such as increased productivity through better education and health levels. Households would save some money from the discontinuation of kerosene lamps for indoor usage and potentially flashlights for near outdoor usage. Those households that run businesses out of their homes may also benefit through greater productivity (Dhungel 2009).

Environmental

Providing reliable electricity should reduce pressure on surrounding forests by decreasing collection of firewood for cooking purposes.

Financial

Electricity tariffs are as follows (Dhungel 2009):

Angakhola - $0.015 per Watt per month
Daunekhola - $0.009 per Watt per month
Tikhedhunga - $0.014 per Watt per month for hotels
- $0.009 per watt per month for households

The annual revenue for the three micro hydro schemes is shown in Table 5.

Table 5 – Annual Revenue for the Three Nepalese Micro Hydro Schemes (Dhungel 2009)

MH System	Return from Household Uses ($)	Return from Industrial Uses ($)	Total Revenue ($)	Return per Installed kW ($)
Angakhola MH	554	0	554	111
Daunekhola MH	703	454	1,157	106
Tikhedhunga MH	5,151	0	5,151	129

Since Dingboche village should most closely resemble Tikhedhunga's blend of hotels and households, we can assume a return of $130 per year per installed kW at Dingboche.

Summary Results, Benefit/Cost Ratios

Subtracting the estimated O&M costs from the anticipated returns for the micro-hydro system leads to a value that will be called the "remaining for breakeven" value. The line item "remaining for breakeven" tells us the maximum allowable annualized construction financing cost that the project can have before the costs outweigh the financial benefits, i.e. before the benefit-cost ratio dips below 1.

Return: $130/kW/yr
O&M Cost: $82/kW/yr
Remaining for breakeven: $48/kW/yr

The breakeven cost results in an allowable annualized construction finance cost of $9,600 ($48/kW*200 kW). Assuming a 6% real interest rate and 15 year project life cycle (Dhungel 2009), the project cost cannot exceed approximately $93,000. However, the estimated project cost is roughly a magnitude higher than this amount. Project costs must be supported through subsidies and grants to increase the feasibility of the project. It should also be noted that the project could become more feasible by charging higher tariffs for electricity.

As discussed above, the estimated capital costs per kW could range from $2,000 to $6,633, or $400,000 to $1,326,600 for a 200 kW project. Assuming a breakeven capital cost of $93,000, subsidies and grants would have to account for anywhere from 76.7% to 93.0% of the project capital cost. Alternatively, doubling the tariffs would result in a return of $260/kW, a "remaining for breakeven" value of $178/kW, and an annualized construction finance cost of $35,600. Using the same assumptions above, the project cost could reach $346,000 before the benefit-cost ratio falls below 1. In this case, subsidies and grants would have to account for anywhere from 13.5% to 73.9% of the project capital cost. Since the original return and tariff assumptions were based on tariffs at Tikhedhunga, note that doubling of the tariffs would cost approximately $0.028 per Watt per month for hotels and trekkers, and $0.018 per Watt per month for households.

Funding Sources to Reduce Shortfall

Subsidies (NGOs, GoN)

The major donor international agencies providing support for the development of the micro hydro sector in Nepal are the Danish Aid Agency, Norwegian Aid Agency, US Agency for International Development, United Nations Development Program, The World Bank and the German Aid Agency (Dhungel 2009).

Grants (Nepal Ag Bank, other sources?)

The Rural Energy Development Program (REDP) of Nepal provides subsidies of Rs. 15000 per household but not exceeding 125000 Rs./kW (http://www.redp.org.np/phase3/subsidy.php). Applying the exchange rate of 70.43 Rs. per 1 USD, Dingboche could qualify for $10,649 from REDP.

Loans (Private or else public Nepalese sources)

The Agricultural Development Bank of Nepal (ADB/N) and Rastriya Banijya Bank are the two major financing institutions supporting the micro hydro sector. Recently, a new financing institution called the Clean Energy Development Bank has been established to serve the energy sector in Nepal (Dhungel 2009).

Case Studies

Daunekhola (12 kW) received a grant from REDP as well as training of local personnel. Community members put up some equity for the project. A subsidy was also provided by the GoN. A loan from the ADB/N was also provided. Subsidies and grants accounted for 59% of capital cost (Dhungel 2009).

The Tikhedhunga system (40 kW) is being financed through funds received from the British Embassy and ACAP. There was also a government subsidy as well as loans and some financial participation by local communities. Subsidies and grants accounted for 70% of total cost (Dhungel 2009).

Angakhola (5 kW) is privately owned. The owner obtained a loan of $1077 from the ADB/N and also received a subsidy from the government for installation of the system. Subsidy was equivalent to 30% of capital cost (Dhungel 2009).

Imja Assistance

As noted in the case studies, similar Nepalese micro-hydro schemes received from 30-70% subsidies and grants for the micro hydro schemes. However, the cost estimates of the micro-hydro alternatives at Dingboche would need further refinement before the financial aid requirements can be determined.

Recommendations for Further Study

The Imja lake region lacks basic hydrology data at both the lake and at Dingboche village (at least it was unavailable to the authors). Seasonal flow rates, year-round ice conditions, and lake inflows are just a few of the hydrologic questions that need answering.

The micro hydro alternatives presented in this report are secondary to the safe drawdown of Imja Lake. As such, the detail of the micro hydro alternatives is limited until further refinement of the drawdown alternatives is achieved.

The electricity demand of the village has been estimated at 5 kW, which appears justified based on similar consumption rates for other remote villages in Nepal. However, the Dingboche Bidhyut Co. (2009) study cites a turbine capacity of 200 kW. Tourism likely would not require such large units. Industrial or agricultural uses could account for more capacity, but 200 kW still seems high given the other Nepalese case studies. The justification for 200 kW needs to be clarified.

Conclusion

The paper combines background data on Imja Lake with information on GLOFs and micro-hydro potential to assess the danger that Imja Lake poses to downstream villages and determines what benefits might be accrued from the controlled drawdown of the lake.

While there remain many unknowns and recommendations for further study, the results show that there are several potential alternatives for stabilizing or drawing down Imja Lake, while also adding hydropower to the process. Doing so will benefit nearby villages and further the Government of Nepal's goal of electrifying the rural areas of the country.

References

Bajracharya, B., Shrestha, A.B., Rajbhandari, L. 2007. Glacial lake outburst floods in the Sagarmatha region. *Mountain Research and Development* 27, 336–344.

Dhungel, Prateek. 2009. *Financial and Economic Analysis of Micro-Hydro Power in Nepal*.

Dingboche Bidhyut Company Ltd. 2009. *Imja Hydropower Project: Desk Study Report.* Submitted to Department of Electricity Development (DOED), Ministry of Energy, Government of Nepal.

French, M.J., and Widden, M.B. 2001. The exploitation of low-head hydropower by pressure interchange with air, using siphons. *Proceedings of the Institution of Mechanical Engineers – Part A – Power and Energy* 215, 223-230.

Hambrey, Michael J., Quincey, Duncan J., Glasser, Neil F., Reynolds, John M., Richardson, Shaun J., and Clemmens, Samuel. 2008. Sedimentological, geomorphological and dynamic context of debris-mantled glaciers, Mount Everest (Sagarmatha) region, Nepal. *Quaternary Science Reviews* 27, 2361-2389. www.elsevier.com/locate/quascirev.

Khennas, Smail, and Barnett, Andrew. 2000. *Best practices for sustainable development of micro hydro power in developing countries.*

Nouni, M.R., Mullick, S.C., and Kandpal, T.C. 2007. Providing electricity access to remote areas in India: An approach towards identifying potential areas for decentralized electricity supply. *Renewable and Sustainable Energy Reviews* 12, 1187-1220 (2008).

Reynolds, J.M., Dolecki, A., and Portocarrero, C. 1998. The construction of a drainage tunnel as part of glacial lake hazard mitigation at Hualcán, Cordillera Blanca, Peru. *Geological Society, London, Engineering Geology Special Publications* 15, 41-48.

Rural Energy Development Program. http://www.redp.org.np/phase3/subsidy.php.

Sakai, A., Fujita, K., and Yamada, T. 2005. *Expansion of the Imja glacier in the east Nepal Himalayas.* 7th GLACKIPR symposium. http://arhiv.rgo-speleo.ru:8179/WWW/rgo/books/glacier_karst7/shakaj_2_74_79.pdf

Toshiba Engineering. 2002. Hydro-eKids Micro Hydro Power Generating Equipment, Hydro eKids. http://al-energy.com/ekids.pdf or http://www.tic.toshiba.com.au/hydro-ekids__8482_/

Watanabe, T., Lamsal, D. and Ives, J.D. 2009. Evaluating the growth characteristics of a glacial lake and its degree of danger of outburst flooding: Imja Glacier, Khumbu Himal, Nepal. *Norsk Geografisk Tidsskrift!Norwegian Journal of Geography* 63, 255-267. Oslo. ISSN 0029-1951.